Ice-Ocean Thermodynamic Interface and Small-Scale Issues

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Talk Overview

- Stefan condition
- Lower boundary condition of mushy layers
- Salt flux to ocean from gravity drainage
- Distribution of salt flux in the ocean
- Under ice melt ponds and false bottoms
- Basal ablation
- Discussion

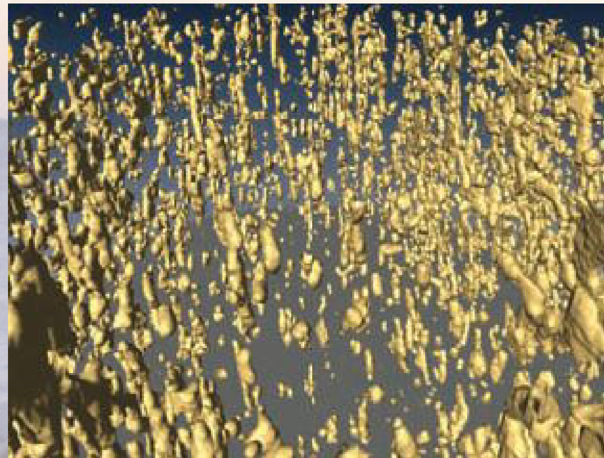
Stefan condition

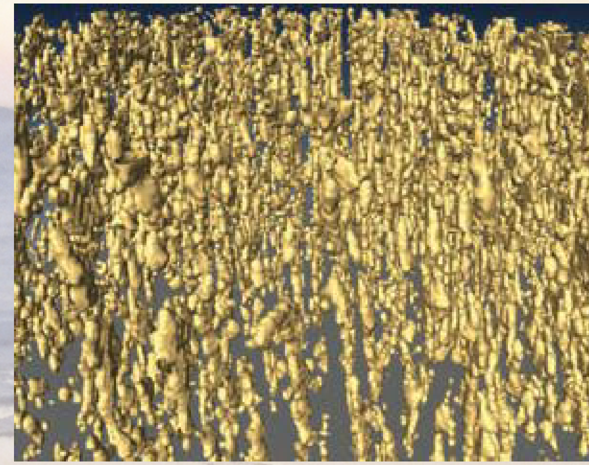
- Sea ice basal growth/ablation is a Stefan problem
- Growth rate given by balance of heat fluxes at the lower ice interface:

$$\rho L \dot{h} = k_i \left.\frac{\partial T}{\partial z}\right|_{ice} + \alpha_h u_* \rho c_p (T_\infty - T_0)$$

- Heat flux in ocean given by some bulk turbulent formula

Sea ice as a mushy layer

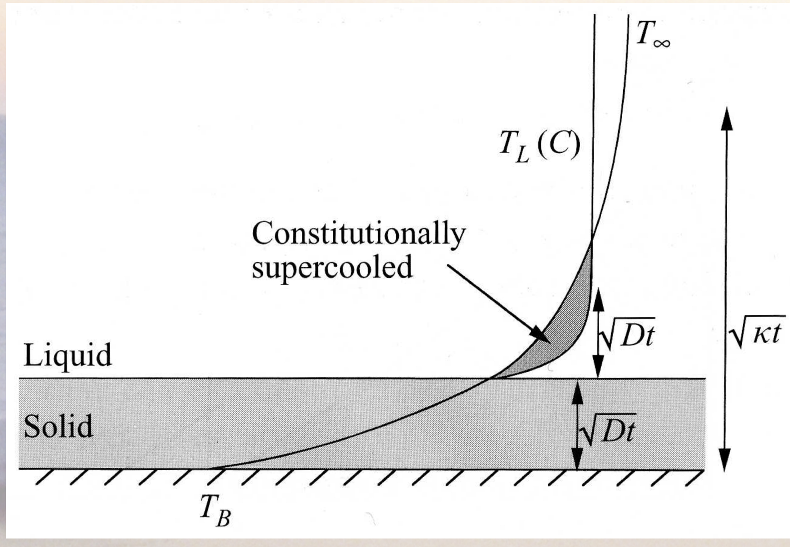




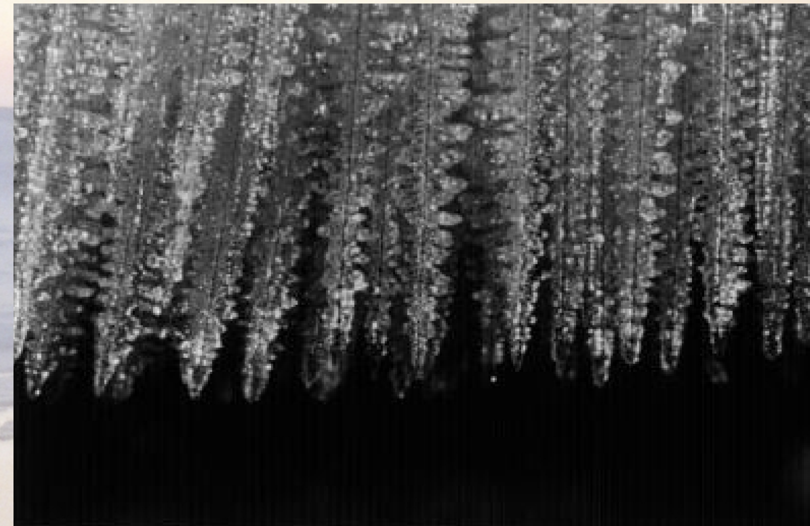
Golden et al. (2007)

- Sea ice consists of small brine inclusions surrounded by pure ice crystal matrix
- Can be treated using mushy layer theory – continuum model of the brine sea ice mixture
- Originally developed for binary alloys such as those that make turbomachinery
- Recently popular as a theoretical model for sea ice

Mushy layer formation



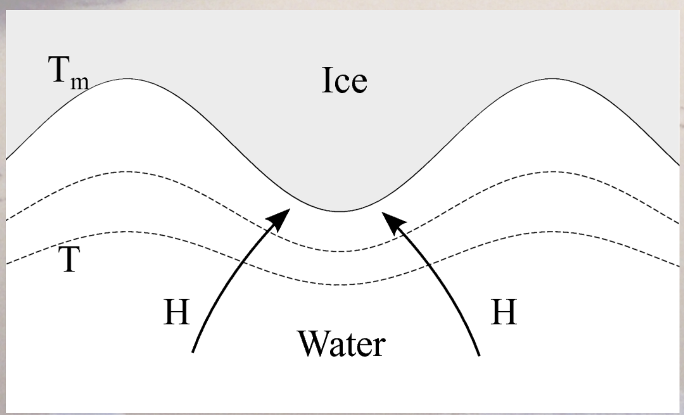
Worster (2000)

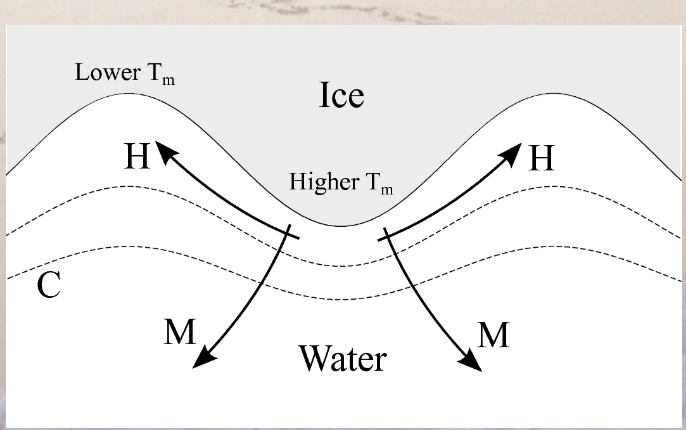


- Growing planar ice rejects all salt ahead of it
- Build up of salt depresses melting temperature ahead of the growing front
- Supercooled region develops – "constitutionally supercooled"

Morphological instability

- Possibility of morphological instability (Mullins & Sekerka 1964)
  - Surface tension stabilizes surface
  - Temperature gradient stabilizes surface
  - Effect of solute on equilibrium melting temperature destabilizes surface





$$\left(\frac{\partial T}{\partial z}\right)_{z=h^+} < -\Gamma \left(\frac{\partial C}{\partial z}\right)_{z=h^+}$$

Temperature gradient　　　　Solute effects

Lower BC for mushy layer during growth

- No clear agreement on what this should be
  - Depends on particular situation
- Popular is the “condition of marginal equilibrium”
  - Mush grows at a speed that just removes constitutional supercooling ahead of the growing interface

$$\left(\frac{\partial T}{\partial z}\right)_{z=h^+} = -\Gamma \left(\frac{\partial C}{\partial z}\right)_{z=h^+}$$

  - This often leads to Φ=0 at the interface, as is usually the case with sea ice
- Some people just use Φ=0 at the interface
- Φ=0 at the interface is annoying – can’t directly use Stefan condition

$$\rho L \phi \frac{dh}{dt} = k_i \left.\frac{\partial T}{\partial z}\right|_{z=h^-} - k_l \left.\frac{\partial T}{\partial z}\right|_{z=h^+}$$

Kinetic effects (1990)

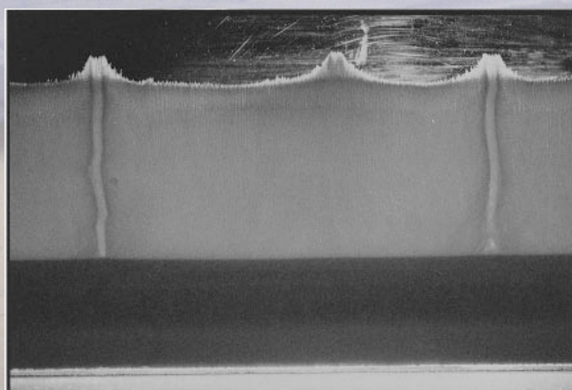
- Although modeled as an equilibrium process, there must be some supercooling at the interface to drive freezing
- Often this is small and it is accurate to model the phase boundary as being at the melting point
- Growth rate for mushy layer diverges as T_∞ approaches T_m
  - Will eventually be limited by kinetic effects $\dot{h} = \varrho(T_L - T_i)$

Practical modeling techniques

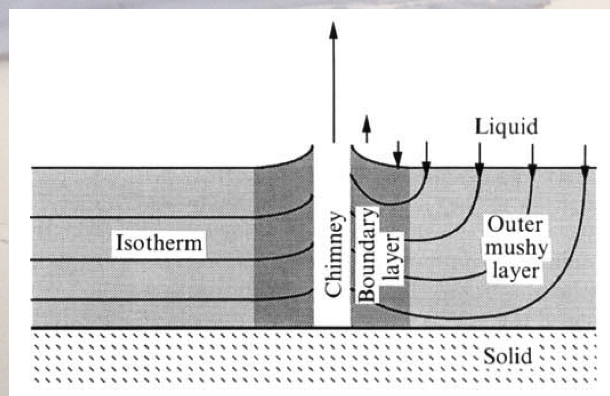
- How to model the lower BC then?
- Problem is often we do not want to waste grid cells in the ocean – yet the BC is in the liquid
- Use a fixed grid and diagnose rather than prognose the interface
- Have Φ equal some small number and tune to observations
- Assume some temperature gradient in the liquid and have an implicit boundary condition and solve iteratively
  - Like the oxygen diffusion problem (Ferris & Hill 1974)
- Top grid cell in ocean model are often at or near freezing point – mushy layer would naively predict too much growth
- Need to take into account turbulence in ocean/frazil formation

Convection in mushy layers

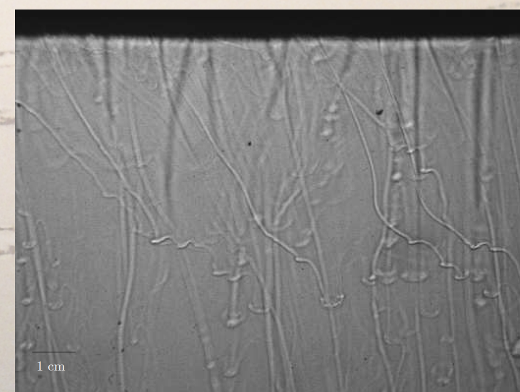
- Cold dense brine overlaying warmer less dense brine during sea ice formation – convective overturning with ocean water
- Downflow through mush dissolves ice crystal matrix – downflow is concentrated in large empty pipes



Worster (2000)



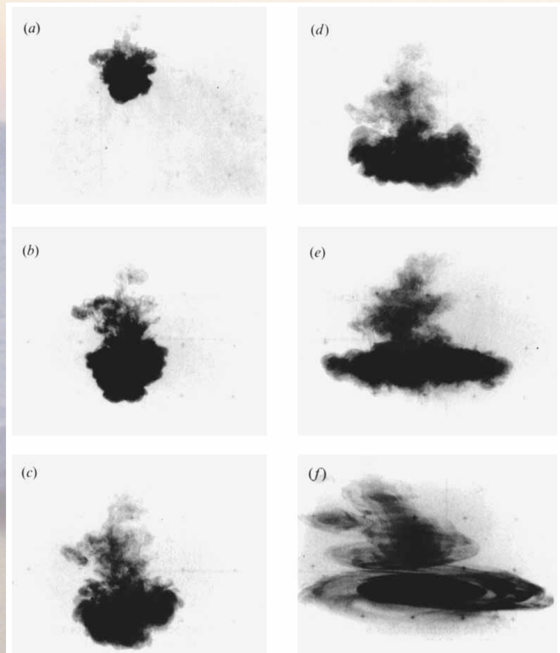
Worster (1991)



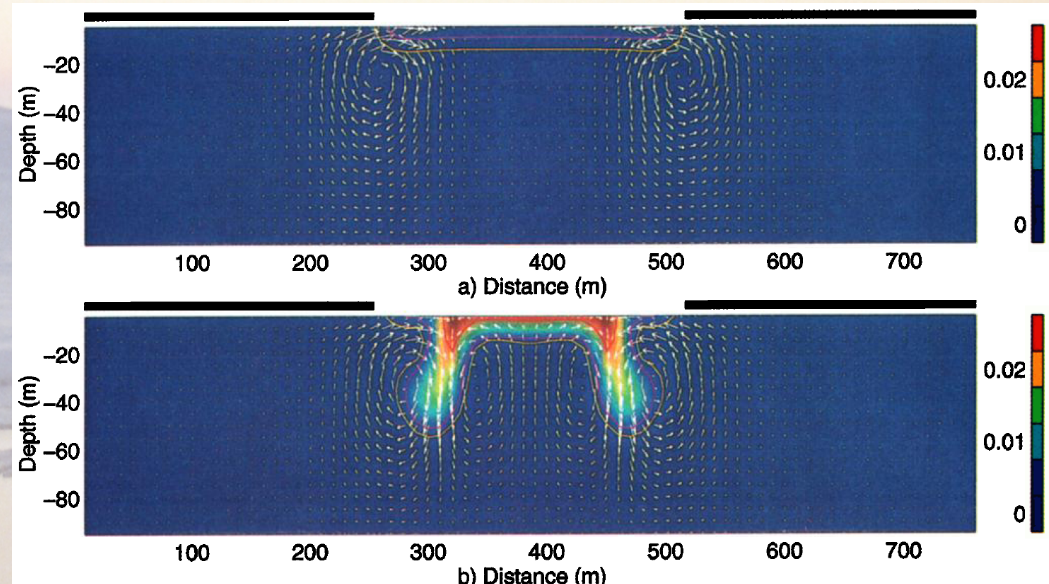
Notz (2005)

- During ice formation salty brine is injected into ocean often in the form of plumes
- Gravity drainage parameterizations give flux of salt to ocean

Salt flux to ocean



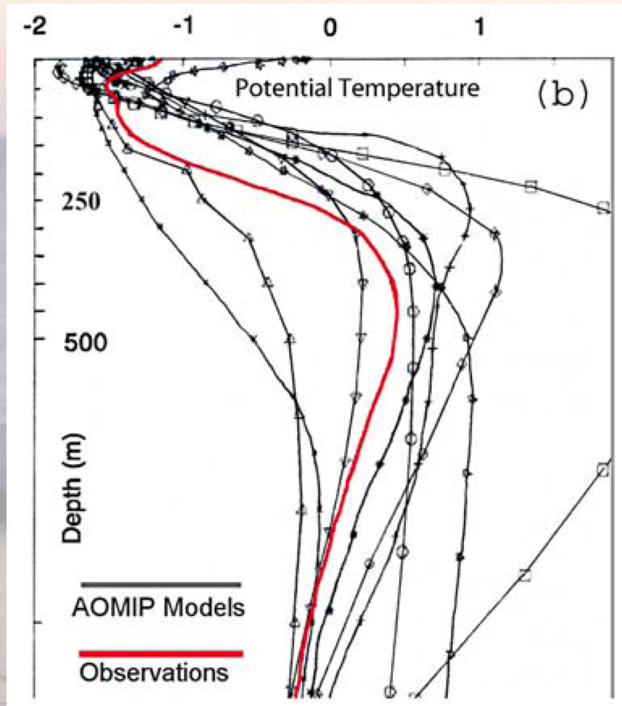
Helfrich (1994)

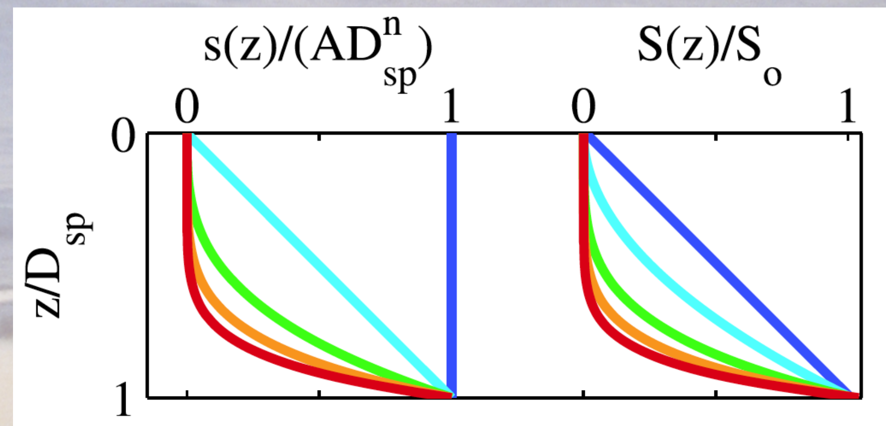


Smith & Morrison (1998)

- Rejected brine is saltier and denser than ocean – sinks to level of neutral buoyancy while mixing with ambient water
- Ice production in a lead produces inhomogeneous brine flux – generates larger scale flow within the ocean as the brine sinks

Salt flux to ocean

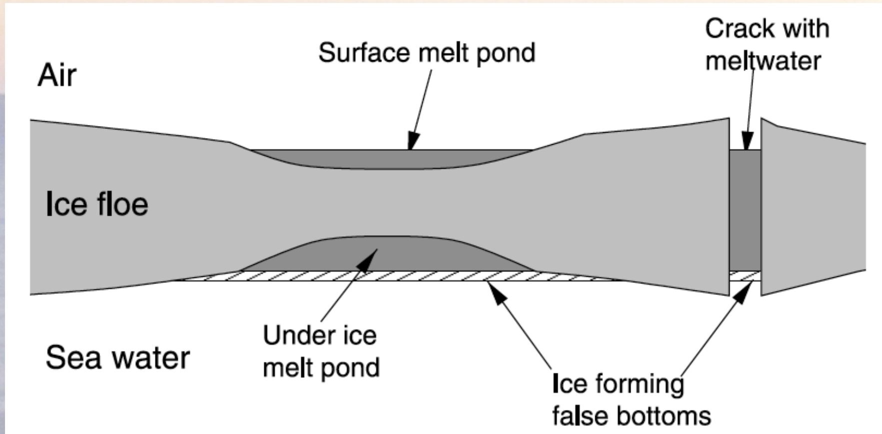




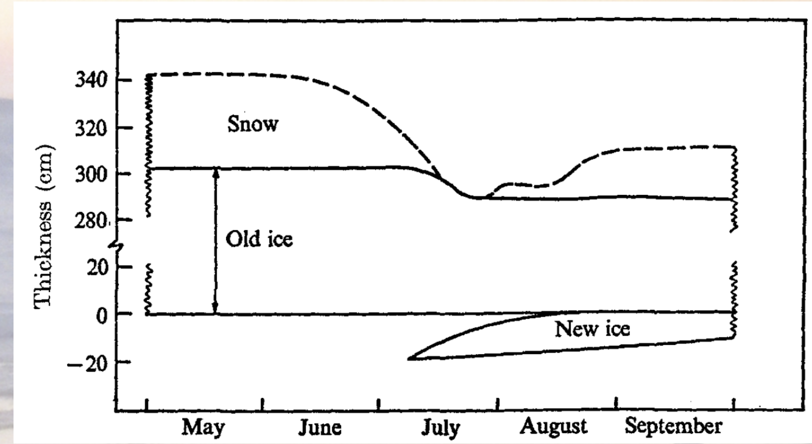
Nguyen et al. 2009

- Improper representation of salt flux explains poor representation of halocline in ocean models?
- Nguyen et al. 2009 used a parameterization of the vertical flow and mixing of rejected salt to improve ocean model representation of halocline

Under-ice melt ponds



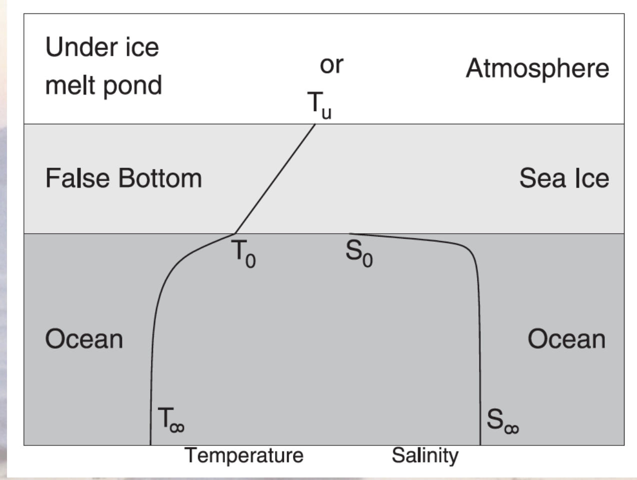
Notz (2003)



Martin & Kauffman (1974)

- Fresh melt water is less dense than sea water so it collects in concavities and cracks under ice
- Double diffusive processes at interface
- Formation of ice between freshwater lens and sea water – false bottom
- Hard to say how prevalent – 5%-10% by area during melt season?

Basal ablation



Notz et al. (2003)

- Saline sea is below the melting temperature of relatively fresh ice – basal ablation can be thought of as dissolution rather than melting
- Ablating ice freshens ocean at interface – raises melting temperature until is equal to the ice melting temperature
- Ablation is rate limited by speed of salt diffusion to interface – ablation slows as interface gets too fresh
- Salt/heat fluxes in ocean will be turbulence driven in the ocean

Basal ablation

- Heat balance at interface

$$\rho L\dot{h} = k_i \left.\frac{\partial T}{\partial z}\right|_{ice} + \alpha_h u_* \rho c_p (T_\infty - T_0)$$

- Salt balance at interface

$$\dot{h}(S_0 - S_i) = \alpha_s u_* (S_\infty - S_0)$$

- Liquidus at interface

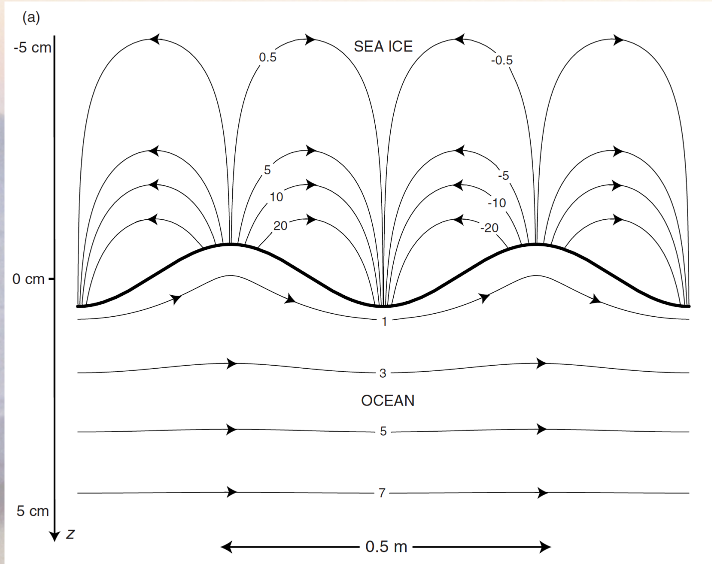
$$T_0 \approx -mS_0$$

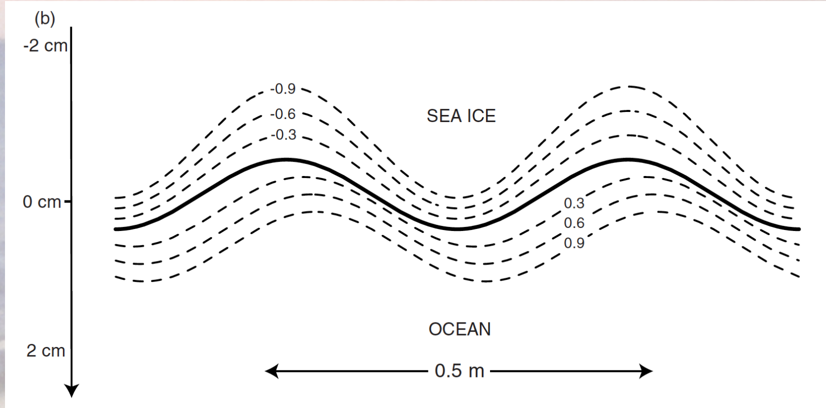
- Three equations, three unknowns (S_0, T_0, dh/dt)
- Solve a quadratic for any of them
- Heat flows much more quickly than salt $\alpha_h \gg \alpha_s$

Other processes…

- Other processes not mentioned
- Lateral melting
- Effect of keels – stirring
- Formation of sea ice from frazil (turbulent conditions)/other more realistic conditions
- Discussion!

Flow induced corrugations





Feltham et al. (2002)

- Flow past underside of ice can cause instability in surface that can create corrugations
- External flow drives an internal flow in the mush – this alters temperature structure in ice
- Effect of external flow is to move corrugations downstream
- Most likely to occur for wind driven costal polynas – fast relative movement of ice and rapid ice formation